Top quark mass measurements at the DØ experiment

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Abstract. The most recent measurements of the top quark mass at the DØ experiment are summarized. Different techniques and final states are used and the top quark mass is determined to be $m_{\mathrm{top}} = 172.8 \pm 1.6(\mathrm{stat} + \mathrm{syst})\mathrm{GeV}/c^2$. In addition, a new, indirect measurement comparing the measured cross section to theoretical calculations is discussed. Both, the direct and the indirect measurement of the top quark mass are in good agreement.

1. Introduction

The top quark is the heaviest of all known fundamental particles. Due to its high mass, the Yukawa coupling of the top quark to the Higgs boson is close to unity suggesting that it may play a special role in electroweak symmetry breaking [1]. Moreover, precise measurements of its mass constrain the mass of the yet-unobserved Higgs boson through radiative corrections to the weak coupling and allow for a restriction of possible extension to the Standard Model [2].

At the Tevatron collider with a centre-of-mass energy of 1.96 TeV, 85% of the top quark pairs are produced in quark-antiquark annihilation; 15% originate from gluon fusion. Both, top and antitop are predicted to decay almost exclusively to a W boson and a bottom quark. According to the number of hadronic W decays, top quark events are classified into all-jets, lepton+jets and dilepton events.

The lepton+jets channel is characterized by four jets, one isolated, energetic charged lepton[1] and missing transverse energy. With 30%, the branching fraction of the lepton+jets channel is about seven times larger than the one of the dilepton channel whereas the signal to background ratio is about three times smaller. The main background in this final state comes from $W + $ jets events. Instrumental background arises from events in which a jet is misidentified as an electron and events with heavy hadrons that decay into leptons which pass the isolation requirements.

The topology of the dilepton channel is described by two jets, two isolated, energetic charged leptons and significant missing transverse energy from the undetected neutrinos. The dilepton channel has the smallest branching ratio but also the smallest background contamination. The main backgrounds are $Z + $ jets and diboson events ($WW + $ jets, $WZ + $ jets, $ZZ + $ jets) as well as instrumental background as characterized above.

At the DØ experiment, two different techniques are used to measure the top quark mass in the dilepton final state: the Neutrino Weighting method [3] and the Matrix Element method [4]. The latter one is also used in the lepton+jets final state where the mass of the hadronically decaying W boson yields an additional constrain to determine the jet energy scale[2] and the

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[1] Here and throughout this article, lepton refers to electron or muon.

[2] In this context, jet energy scale refers to an additional scalar correction factor on top of the nominal jet energy correction applied at the DØ experiment.

top quark mass simultaneously and to achieve a significant reduction of the main systematic uncertainty [5]. Complementary, the top quark mass can be extracted from the measured top pair production cross section comparing it to theoretical calculations [6].

2. The Neutrino Weighting Method

The Neutrino Weighting method is a template based method and has already been used during the Run I period of the Tevatron accelerator. For each event, the neutrino momenta are calculated assuming a certain top mass and different neutrino pseudorapidities. A weight w is assigned according to the agreement of the calculated sum of the neutrino momenta $\sum_{i=1}^{2} p_x^{\nu_i}$, $\sum_{i=1}^{2} p_y^{\nu_i}$, and the measured missing transverse momentum components $\not{E}_x, \not{E}_y$ in the event, given by

$$w = \exp\left(\frac{-(\not{E}_x - \sum_{i=1}^{2} p_x^{\nu_i})^2}{2\sigma_{\not{E}_x}^2}\right) \exp\left(\frac{-(\not{E}_y - \sum_{i=1}^{2} p_y^{\nu_i})^2}{2\sigma_{\not{E}_y}^2}\right), \qquad (1)$$

where $\sigma_{\not{E}_x}, \sigma_{\not{E}_y}$ denote the resolution of the missing energy measurement. This process is repeated many times varying the jet and lepton energies within their experimental resolution. Next, signal probability distributions as a function of the top quark mass, the mean and the RMS of the weight distributions are derived using Monte Carlo simulated signal events of different top quark masses. To reduce the bias from background, background probability distributions as a function of the mean and the RMS of the weight distributions are determined accordingly using simulated Z + jets and diboson events. Finally, a likelihood function that consists of three terms is built to measure the top quark mass. The first term accounts for the agreement of the expected number of signal and background Monte Carlo events to the one in the data sample, the second for the agreement of the background events with the prediction, and the third for the agreement of the data with the signal and background probability distributions. The method is calibrated using ensemble tests.

For the measurement, events in the dilepton final state are selected requiring two isolated leptons, or alternatively one isolated lepton and one isolated, charged particle track. The data set analyzed corresponds to an integrated luminosity of about 1 fb^{-1} collected between April 2002 and February 2006. A kinematic selection that reduces the contamination from background to about 20% is applied. The top quark mass is extracted from 82 top pair candidate events yielding

$$m_{\text{top}} = 176.0 \pm 5.3(\text{stat}) \pm 2.0(\text{syst}) \text{ GeV}/c^2. \qquad (2)$$

The main systematic uncertainties on this measurement come from the energy scale of the jets, the modeling of the simulated signal events and the fragmentation of the jets from b quarks.

3. The Matrix Element Method

The Matrix Element method was developed at the DØ experiment during the Run I period of the Tevatron to extract the top quark mass with high precision from a sample of low statistics [7]. The Matrix Element method yields the single most precise measurement of the top quark mass.

The probability for a final state $y = (p_1, \ldots, p_6)$ of 6 partons of four-momenta $p_i, i = 1, \ldots, 6$ to originate from the signal process under the assumption of a certain top mass m_{top} is given by

$$P_{\text{sgn}}(x; m_{\text{top}}) = \frac{1}{\sigma_{\text{obs}}(m_{\text{top}})} \int d\epsilon_1 \, d\epsilon_2 \, f_{\text{PDF}}(\epsilon_1) \, f_{\text{PDF}}(\epsilon_2) \, \frac{(2\pi)^4 \, |M(y)|^2}{\epsilon_1 \epsilon_2 s} \, d\Phi_6 \, W(x, y) \,, \quad (3)$$

where ϵ_1, ϵ_2 denote the energy fraction of the incoming quarks from the protons and antiprotons, f_{PDF} the parton distribution function, s, the centre-of-mass energy squared, $M(y)$, the leading-order matrix element [8] and $d\Phi_6$, an element of the 6-body phase space. The finite detector resolution is taken into account using a transfer function $W(x, y)$ that describes the probability

of a partonic final state y to be measured as $x = (\tilde{p}_1, \ldots, \tilde{p}_n)$ in the detector. The signal probability is normalized with the observable cross section σ_{obs}.

In a similar way, for each event the probability to arise from background is calculated. Taking the huge amount of computing time into account, only the leading source of background is considered, i.e. Z+jets probabilities in the dilepton case, W+jets probabilities in the lepton+jets channel. In a last step, both probabilities, signal and background, are combined to an event probability taking the signal fraction f_{top} into account

$$P_{\text{evt}}(x; m_{\text{top}}) = f_{\text{top}} \cdot P_{\text{sgn}}(x; m_{\text{top}}) + (1 - f_{\text{top}}) \cdot P_{\text{bkg}}(x), \qquad (4)$$

and the top quark mass is extracted from a likelihood fit of the product of the event-by-event probabilities. To calibrate the method and correct for any bias, Monte Carlo simulated events are used to perform ensemble tests.

3.1. Dilepton Channel
While only events with exactly one electron and exactly one muon are taken into account so far, the measurement makes use of the full Run II data set recorded between April 2002 and May 2008. This corresponds to an integrated luminosity of 2.8 fb^{-1}. To reduce the fraction of background events, a kinematic selection is applied leaving 107 top pair candidate events with a signal fraction of about 80%. The top quark mass is measured to be

$$m_{\text{top}} = 172.9 \pm 3.6(\text{stat}) \pm 2.3(\text{syst}) \text{ GeV}/c^2. \qquad (5)$$

The dominant sources of systematic uncertainties are jet uncertainties, such as their energy scale and resolution. With an statistical uncertainty of 3.6 GeV, this measurement has the smallest uncertainty of all top mass measurements performed in the dilepton channel at the DØ experiment.

3.2. Lepton+Jets Channel
As stated above, the largest systematic uncertainty on the top quark mass arises from the jet energy scale. Since one of the W boson decays hadronically in the lepton+jets channel, the well known W mass can be used to constrain the jet energies. An additional scale factor is introduced in Eq. (3) and both, the top quark mass and the jet energy scale are measured simultaneously.

In the lepton+jets channel, an integrated luminosity of 2.2 fb^{-1} is used. A kinematic selection leaves 491 data events in total, the signal fraction is about 40%. The top quark mass in this sample is measured to be

$$m_{\text{top}} = 172.2 \pm 1.0(\text{stat} + \text{JES}) \pm 1.4(\text{syst}) \text{ GeV}/c^2. \qquad (6)$$

The systematic uncertainty is dominated by the uncertainty on the difference between the nominal inclusive response and the response of jets from b quarks in the calorimeter.

4. Top Quark Mass From Production Cross Section
Two different schemes are commonly used to define the top quark mass: the $\overline{\text{MS}}$ and the pole mass definition. Direct top quark mass measurements are based on leading-order Monte Carlo generators where the top quark is described by a Breit-Wigner resonance and the measured mass corresponds only approximately to a pole mass. Since the top quark pair production cross section depends on the top quark mass, a measurement with a well-defined and renormalization-scheme independent mass definition can be realized comparing the results from cross section measurements to fully inclusive calculations in higher-order QCD. Here, the pole mass definition is applied and the extracted value can be unambiguously interpreted. Comparing

the combined measured cross sections from the lepton+jets, dilepton and lepton+tau channel to the NLO+NNLL calculations from S. Moch *et al.* [9] yields a top quark mass of $169.6^{+5.4}_{-5.5}$ GeV$/c^2$, while the comparison with the NLO+NLL calculations from M. Cacciari *et al.* [10] yields $167.8^{+5.7}_{-5.7}$ GeV$/c^2$. Both results are in good agreement with the direct measurements.

5. Conclusion

The top quark mass has been measured at the DØ experiment in different final states using different techniques. In the dilepton channel, the largest systematic uncertainty arises from the jet energy scale. This has been addressed in the lepton+jets channel with a simultaneous measurement of the top quark mass and the jet energy scale which is well constrained by the mass of the hadronically decaying W boson. Combining all measurements with the Best Linear Unbiased Estimate (BLUE) [11], the top quark mass is determined at the DØ experiment to be

$$m_{\text{top}} = 172.8 \pm 1.6(\text{stat} + \text{syst}) \text{ GeV}/c^2. \tag{7}$$

The top quark mass has also been extracted from cross section measurements comparing them to fully inclusive calculations in higher-order QCD. Both measurements, direct and indirect, are in good agreement with each other.

Acknowledgments

References

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